A Coupled Multi-Physics Model for Dynamics of Offshore Wind Energy Converter

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Abstract

The coupled multi-physics model for offshore wind turbine system has been developed and presented in this paper. The subsystem models are developed initially separately and coupled together based on the partitioned method. The multi-physics model consists of four subsystems, structural dynamics of turbine, described by finite element method, aero dynamics of wind which is modelled based on blade element momentum and dynamics stall model, hydro-dynamics of wave which is modelled based on boundary element method and soil dynamics of sea bed is modelled based on a coupled of finite element and scaled boundary finite element. The software components communicate with the so called Component Template Library (CTL). The simulation of entire model of offshore wind turbine is performed in time domain and results are presented at the end of this paper.

Keywords

Multiphysics; Offshore Wind Turbine; FEM; BEM; SBFEM

Introduction

Due to the increasing requirement for energy over the world, humans always seek new sources of energy having no impact to environment. The wind energy technology is a renewable energy technology which has less impact on environment. In history, wind turbine was used only for agriculture. As people are concerning and searching for new sources of energy, the development of wind turbine for running the electrical power generator is initialized. In the long period of research and development, wind turbine is relatively small in the past compared to present turbine. Previously, there were turbines with rotor diameter of 10 meters; while presently they are very large and more flexible, the diameter of rotor is 120 meters and 100 meters height for the tower.

Wind farms are generally located on the area of strong wind speed such as on mountain areas. They are usually called land-based wind turbine farms. Due to the higher expected energy, wind farms are moved from land to offshore as the wind speed is higher there. In order to anlyze wind turbine in offshore condition, the coupling of different physical fields are necessary. Here we present how to model such kind of the problem.

Entire Model of Offshore Wind Turbine

The model of an offshore wind turbine consists of four sub-models, the aerodynamics of wind, the structure dynamics of turbine components, the hydrodynamics of the ocean wave and the soil dynamics of unbounded soil, see in Fig. (1). All sub-models are developed initially separately and finally coupled via the partitioned method. The descriptions of each sub-model are as follow; the structural subsystem, which is a nonlinear large displacement finite element model (FEM); the aerodynamic subsystem which describes stochastic wind and includes instationary dynamic stall model for the aeroelastic blade loading; the hydrodynamic subsystem, modelled mainly as potential flow and couple to the stochastic wave field to describe the real sea state, the computations on this part based on the boundary element method (BEM); and the soil dynamic subsystem modelled as near-field soil near the underground structure discretized by FEM and far-field effects included by the scaled boundary finite element method (SBFEM).

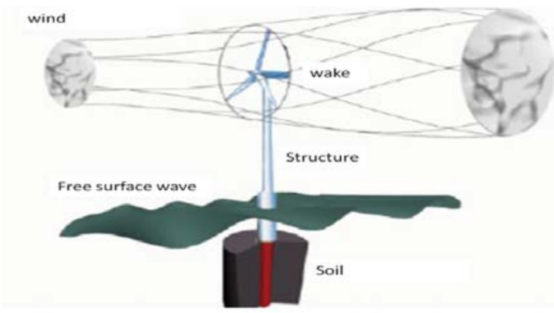

FIG. 1 ENTIRE MODEL OF OFFSHORE WIND TURBINE

All of these models are coupled in time domain, and the consistent simulation of the offshore wind turbine can be performed based on partitioned method.

Structural Dynamics of Turbine

On the structural dynamics part, we followed previous research from our institute. The geometrical nonlinear formulations of the beam are used for dynamics of structure. The structure of turbine is initially seperately modeled in substructure level, three blades structure for rotor system, tower system and foundation system.

Formulation of Coupled Substructure System

First of all, we focus on the rotor system. The rotor has three blades. Each blade has the variable $\boldsymbol{q}^i$ associated with it, where (i = 1, 2, 3) denoting the three blades. The variable $\boldsymbol{q}^i$ is represented by a coupling variable (subscript c) and the free variables (subscript f) as shown below

$$\boldsymbol{q}^i = \begin{bmatrix} \boldsymbol{q}_c^i \\ \boldsymbol{q}_f^i \end{bmatrix}. \tag{1}$$

Similarly, the tangential stiffness $\boldsymbol{D}^i$ and the force vector $\boldsymbol{g}^i$ for each blade are as follow

$$\boldsymbol{D}^i = \begin{bmatrix} \boldsymbol{D}_c^i \\ \boldsymbol{D}_f^i \end{bmatrix}, \tag{2}$$

$$\boldsymbol{g}^i = \begin{bmatrix} \boldsymbol{g}_c^i \\ \boldsymbol{g}_f^i \end{bmatrix}. \tag{3}$$

The blades are rigidly coupled to each other, each blade has its own coordinate system. We choose one blade (i = 1) as the reference coordinate system for the rotor system. The transformation of this reference system into other two blades (i=2,3) can be performed with the transformation matrix $\widetilde{\boldsymbol{N}}_2^1$ and $\widetilde{\boldsymbol{N}}_3^1$. The variables are given by $\boldsymbol{q}^1 = \widetilde{\boldsymbol{N}}_2^1\boldsymbol{q}^2$ and $\boldsymbol{q}^1 = \widetilde{\boldsymbol{N}}_3^1\boldsymbol{q}^3$, where $\widetilde{\boldsymbol{N}}$ is transformation matrix, see more details in reference. After rewrite the formulation above yields the coupled system of rotor blade.

$$\boldsymbol{D}^r\boldsymbol{q}^r = \boldsymbol{g}^r, \tag{4}$$

where $\boldsymbol{g}^r = \begin{bmatrix} \boldsymbol{g}_c^1 + \widetilde{\boldsymbol{N}}_2^1\boldsymbol{g}_c^2 + \widetilde{\boldsymbol{N}}_3^1\boldsymbol{g}_c^3 \\ \boldsymbol{g}_f^1 \\ \boldsymbol{g}_f^2 \\ \boldsymbol{g}_f^3 \end{bmatrix}, \boldsymbol{q}^r = \begin{bmatrix} \boldsymbol{q}_c^1 \\ \boldsymbol{q}_f^1 \\ \boldsymbol{q}_f^2 \\ \boldsymbol{q}_f^3 \end{bmatrix}.$

Now the rotor system has to be coupled to the tower system (numbered i = 0) according to the assumption that the rotor blade can freely rotate about the axis (the axis of wind direction). The axis of the wind direction may be defined as the X-direction of the coordinate system (i = 0) of the tower. During the computation, the transformation from the rotor coordinate system (system i = 1) to the tower coordinate system (system i = 0) is required. This transformation can be done in two steps; the first is to transform from the rotor system to the intermediate reference system (index a) at the coupling node, while the second is to transform from the intermediate reference to the tower system (system i = 0), $\boldsymbol{N}_1^0 = \boldsymbol{N}_a^0\boldsymbol{N}_1^a$ at the coupling node, the transformation can be defined by the following matrix

$$\widetilde{\boldsymbol{N}}_1^0 = \begin{bmatrix} \boldsymbol{N}_1^0 & 0 & 0 \\ 0 & \boldsymbol{N}_1^0(2,2) & \boldsymbol{N}_1^0(2,3) \\ 0 & \boldsymbol{N}_1^0(3,2) & \boldsymbol{N}_1^0(3,3) \end{bmatrix}, \tag{5}$$

with coupled variable $\boldsymbol{q}_c^1 = [u_1, u_2, u_3, \psi_2, \psi_3]^T$.

Finally the coupled system of structures can be achieved by substituting and coupling the variables as shown below

$$\boldsymbol{D}\boldsymbol{q} = \boldsymbol{g}, \tag{6}$$

where $\boldsymbol{D} = \begin{bmatrix} \boldsymbol{D}_{ff}^0 & \boldsymbol{D}_{fc}^0 & 0 \\ \boldsymbol{D}_{cf}^0 & \boldsymbol{D}_{cc}^0 + \widetilde{\boldsymbol{N}}_1^0\boldsymbol{D}_{cc}^r\widetilde{\boldsymbol{N}}_1^{0\,\boldsymbol{T}} & \widetilde{\boldsymbol{N}}_1^0\boldsymbol{D}_{cf}^r \\ 0 & \boldsymbol{D}_{fc}^r\widetilde{\boldsymbol{N}}_1^{0\,\boldsymbol{T}} & \boldsymbol{D}_{ff}^r \end{bmatrix}, \boldsymbol{q} = \begin{bmatrix} \boldsymbol{q}_f^0 \\ \boldsymbol{q}_c^0 \\ \boldsymbol{q}_f^r \end{bmatrix},$

$\boldsymbol{g} = \begin{bmatrix} \boldsymbol{g}_f^0 \\ \boldsymbol{g}_c^0 + \widetilde{\boldsymbol{N}}_1^0\boldsymbol{g}_c^r \\ \boldsymbol{g}_f^r \end{bmatrix}.$

The system of equation above shows the coupled substructure system of turbine components. The same procedure is performed to complete the dynamics equation, in which the effect of rigid body rotation of rotor system is taken into account.

Dynamics Equation of Turbined

The dynamics equation of wind turbine is described by system of partial diferential equation (PDE). The formulations are derived based on geometrical nonlinear of beam, the systems of PDE are shown very brieftly here, more details please refer to reference. The dynamics equation is written in two balance of the momentum, forces due to translation and moment due to rotation.

The balance of forces is

$$\partial_l(\boldsymbol{R}\boldsymbol{n}_e) + \boldsymbol{n}_{ext} = \mu\partial_t^2\boldsymbol{u}, \tag{7}$$

where $\boldsymbol{R}$ is rotational matrix, $\boldsymbol{n}$ is forces. The balance of moment given by

$$\partial_l(\boldsymbol{R}\boldsymbol{m}_e) + \partial_l\boldsymbol{r} \times (\boldsymbol{R}\boldsymbol{n}_e) + \boldsymbol{m}_{ext} = \boldsymbol{R}\big(\widetilde{\boldsymbol{\Upsilon}}\boldsymbol{J}\boldsymbol{\Upsilon}\big) + \boldsymbol{J}\partial_t\boldsymbol{\Upsilon}, \tag{8}$$

The $\widetilde{\boldsymbol{\Upsilon}}$ is the skew symmetric matrix of angular velocity $\boldsymbol{\Upsilon}$, and $\boldsymbol{J}$ is inertia tensor. The Eq.(7) and Eq.(8) are discretized based on conventional FEM. The discrete form of dynamics equation is derived and yields as below

$$\boldsymbol{f_k}(\partial_t^2\boldsymbol{d}, \partial_t\boldsymbol{d}, \boldsymbol{d}, t) + \boldsymbol{f_{in}}(\boldsymbol{d}, t) = \boldsymbol{f_{ext}}(\boldsymbol{d}, t), \tag{9}$$

where $\boldsymbol{f_k}$ denotes inertia forces, in each element the

inertial force given by

$$\boldsymbol{f}_{\boldsymbol{k}}^{\boldsymbol{e}} = \int_{l_k}^{l_{k+1}} \begin{bmatrix} \mu \partial_t^2 \boldsymbol{d} \\ \boldsymbol{T}^T (\boldsymbol{J} \partial_t \boldsymbol{\Upsilon} + \partial_l \boldsymbol{\Upsilon} \boldsymbol{J} \boldsymbol{\Upsilon}) \end{bmatrix}, \tag{10}$$

the internal forces in element can be computed

$$\boldsymbol{f}_{\boldsymbol{in}}^{\boldsymbol{e}} = \int_{l_k}^{l_{k+1}} \begin{bmatrix} \partial_l \boldsymbol{N} \\ \boldsymbol{N} \end{bmatrix} \boldsymbol{v}^T \begin{bmatrix} \boldsymbol{C}_n \boldsymbol{\gamma} \\ \boldsymbol{C}_m \boldsymbol{\kappa} \end{bmatrix}, \tag{11}$$

where $\boldsymbol{v}$ denotes corresponding matrix and $[\boldsymbol{C}_n \boldsymbol{\gamma} \quad \boldsymbol{C}_m \boldsymbol{\kappa}]^T$ denotes corresponding matrix of material. The external forces $\boldsymbol{f}_{\boldsymbol{ext}}$ is interaction force from coupled external system, e.g. wind, wave, sea bed. This forces given by

$$\boldsymbol{f}_{\boldsymbol{ext}}^{\boldsymbol{e}} = \int_{l_k}^{l_{k+1}} \boldsymbol{N}^T \begin{bmatrix} \boldsymbol{R} \boldsymbol{n}_{\boldsymbol{ext}} \\ \boldsymbol{T}^T \boldsymbol{R}^T \boldsymbol{m}_{\boldsymbol{ext}} \end{bmatrix}, \tag{12}$$

where $\boldsymbol{n}_{\boldsymbol{ext}}$ denotes external forces and $\boldsymbol{m}_{\boldsymbol{ext}}$ denotes external moment.

Aerodynamics of Instationary Wind

On dynamics of wind turbine, the aerodynamics of instationary wind are required for computing wind forces along the rotor blade. This part we followed previous research of our institute. The model described local fluid flow through profile of rotor blade. The global flow is also necessary in order to include the wake effect on rotor system.

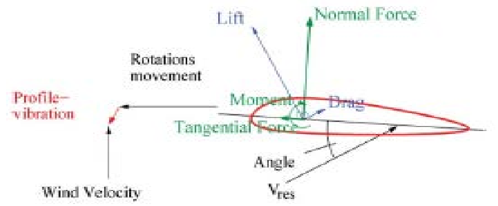

FIG. 2 FORCES ON 2D PROFILE OF ROTOR BLADE

Local Aerodynamics

Fluid flow model describe the flow through rotor blade locally. The forces along 2D profile of rotor blade are reasonably obtained in this case, see in Fig. (2). The drag force (f_d) acting parallel to the relative velocity $(\boldsymbol{v_r})$, while lift force (f_l) is perpendicular, the moment (m_{ae}) applies on 2D profile for take the rotational effect due to local aerodynamics flow. The formulations are given by

$$f_d = \frac{\rho_a}{2} \boldsymbol{v_r}^2 c_d c, \tag{13}$$

$$f_l = \frac{\rho_a}{2} \boldsymbol{v_r}^2 c_l c, \tag{14}$$

$$m_{ae} = \frac{\rho_a}{2} \boldsymbol{v_r}^2 c_m c^2, \tag{15}$$

where ρ_a denotes air density, c is cord length of profile, while c_d, c_l, c_m are drag, lift and moment coefficient, respectively. The relative velocity $(\boldsymbol{v_r})$ is the means of wind velocity, this $(\boldsymbol{v_r})$ includes the effect of rotational movement of rotor and the vibration of rotor blade.

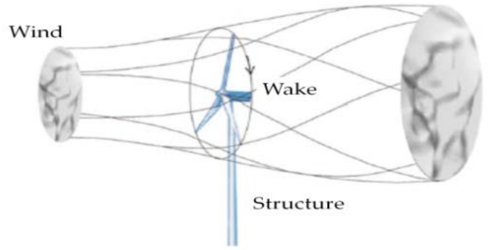

FIG. 3 THE CONFIGURATION OF FLOW FOR WIND TURBINE

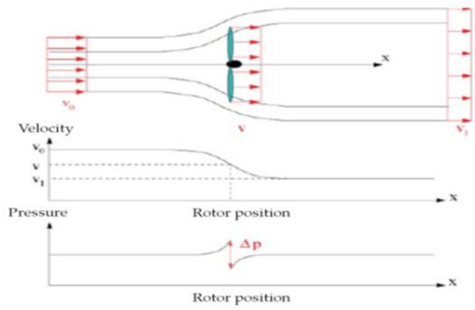

FIG. 4 THE IDEAL FLOW OF ROTOR SYSTEM

Global Aerodynamics

As the global aerodymics of wind turbine is very complicated due to turbulence and vortex behind the rotor (see in Fig. (3)). These physical flow could be modelled and solved them somehow by CFD, however the computational effort is very limited. Here we used the ideal flow of rotor system, under the assumption that no flow in radial direction inside wake and flow is frictionless. The wind speed is reduced from upstream with velocity $\boldsymbol{v_0}$ to down stream with velocity $\boldsymbol{v_1}$. The pressure increase from atmospheric pressure at upsteam position to pressure p at rotor position before it is immediately dropped Δp by the rotor, see in Fig. (4). Again at downstream, the pressure increases to the atmosmeric level. The acting forces on rotor f_{rot} can be obtained by

$$f_{rot} = \Delta p A_{rot}, \tag{16}$$

where A_{rot} denotes area of rotor dish.

The pressure drop Δp can be computed by using Bernoulli's equation from upstream to downstream, which yields the pressure dropp as

$$\Delta p = \frac{1}{2} \rho (\boldsymbol{v_0}^2 - \boldsymbol{v_1}^2). \tag{17}$$

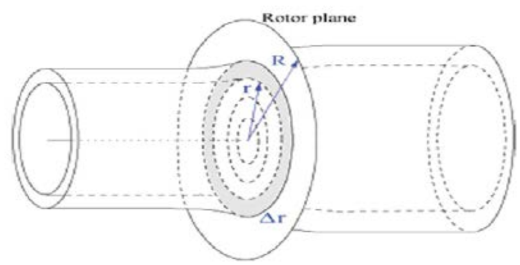

FIG. 5 THE CONTROL VOLUME OF WIND FLOW

Concerning the control volume in Fig. (5), the axial momentum applied to this volume, yields the equation below

$$\rho \boldsymbol{v_1}^2 \boldsymbol{A}_1 + \rho \boldsymbol{v_0}^2 (\boldsymbol{A}_c - \boldsymbol{A}_1) + \partial_t \boldsymbol{m}.\boldsymbol{v_0} - \rho \boldsymbol{v_0}^2 \boldsymbol{A}_c = -F, \quad (18)$$

where $\partial_t \boldsymbol{m}$ is substituted by means of mass conservation. The forces F coming from pressure drop over the rotor, when we substitute force (F) in Eq.(18) by pressure drop from Eq.(17), yield the interesting formulation.

$$\boldsymbol{v} = \frac{1}{2}(\boldsymbol{v_0} + \boldsymbol{v_1}). \quad (19)$$

Eq.(19) shows the physical meaning that the velocity at rotor position can be obtained by means of velocity at upstream and downstream. This makes less computation to obtain the velocity at the rotor blade.

Until now the computing aerodynamics force to rotor blade has presented. These are so-called blade element momentum theory, however, the formulations are suitable for infinite number of rotor blade. When used for finite number of blade, the correcting factor is necessary, which can be obtained by the Plandlt's tip loss factor, more details please refer to reference. Also the instationary of wind can be involved by using dynamics stall model. The systems of ODE are presented to describe the instationary effect of aerodynamics forces as shown in Fig. (6), and there is unnecessary here to go in details, readers please refer to [3] and reference therein.

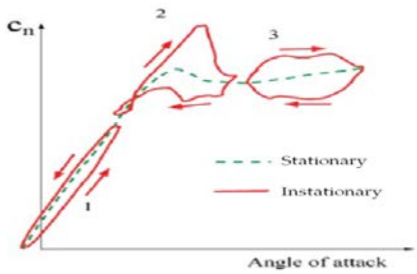

FIG. 6 INSTATIONARY O F AERODYNAMICS COEFFICIENT

In order to complete aerodynamics forces on the blade structure corresponding to FEM in structure part, the aerodynamics forces along the element of the rotor are computed as

$$\boldsymbol{f}_a^e = \int_{l_k}^{l_{k+1}} \boldsymbol{N}^T \begin{bmatrix} \boldsymbol{R}\boldsymbol{n}_{ext} \\ \boldsymbol{T}^T \boldsymbol{R}^T \boldsymbol{m}_{ext} \end{bmatrix}, \quad (20)$$

where $\boldsymbol{R}$ and $\boldsymbol{T}$ are corresponding matrix in FEM. The external forces $\boldsymbol{n}_{ext} = [0, c_f \boldsymbol{f}_t, c_f \boldsymbol{f}_n]$ and external moment $\boldsymbol{m}_{ext} = [c_f \boldsymbol{m}_{ae}, 0, 0]$, where c_f denotes Prandtl's tip loss factor. To complete $\boldsymbol{f}_a^e$ in Eq.(20), there is suitable to integrate numerically. The Grauss point integration scheme is used here, as this reqires only the informations of $\boldsymbol{n}_{ext}$ and $\boldsymbol{m}_{ext}$ at Grauss point in 2D case, see in Fig. (7). The coupled aerodynamics of wind and dynamics of structure is automatically included in the model as mentioned before, in addition, the aerodynamics forces ($\boldsymbol{n}_{ext}$ and $\boldsymbol{m}_{ext}$) are function of relative velocity $\boldsymbol{v}_r$ and aerodymics coefficient (c_d, c_l, c_m). Both are function of displacement , velocity, and acceleration of structure. These mean that when the movement of structure is changed, it influence to wind flow and vortex system. Oppositely when the wind flow is changed, it influences the movement of structure as well.

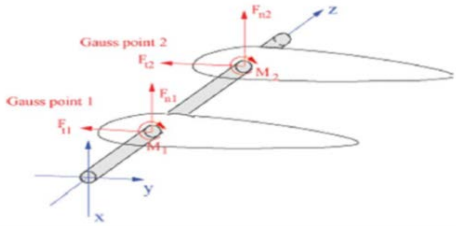

FIG. 7 AERODYNAMICS FORCES AT GRAUSS POINT

Hydrodynamics of Ocean Wave

On the part of ocean wave, we model the fluid flow based on potential theory. The fluid is incompressible, inviscid, irrotational flow and the surface tension is nelegted. The velocity field is obtained from gradient of potential $\boldsymbol{\Phi}$ as $\boldsymbol{v}(\boldsymbol{r},\boldsymbol{t}) = \nabla\boldsymbol{\Phi}$ in any position ($\boldsymbol{r}$) and time ($\boldsymbol{t}$) in fluid domain (Ω_f), where ∇ denotes the spatial gradient reference to the corresponding coordinate system. The fluid inside domain $\boldsymbol{\Omega_f}$ has to be satisfied by so-called Lapace's equation.

$$\Delta\boldsymbol{\Phi}(\boldsymbol{r},t) := \nabla^2\boldsymbol{\Phi}(\boldsymbol{r},t) = 0. \quad (21)$$

The free surface of fluid is described as level set function $F(\boldsymbol{r},t)$. The fluid particles on the free surface are moved together with the free surface movement. The normal velocity of fluid can be computed by

$$\boldsymbol{v}\cdot\boldsymbol{n} = \nabla\boldsymbol{\Phi}\ \cdot\boldsymbol{n} =: \partial_n \nabla^2 \boldsymbol{\Phi}(\boldsymbol{r},t) = -\frac{v\cdot\nabla F}{|\nabla F|}, \quad (22)$$

where $\boldsymbol{n}$ is normal velocity of fluid on surface.

On the free surface, it will be convenient to introduce the coordinate system, in which z-direction is opposite to gravity and point upward from undisturbed x,y plane. The level set function is obtained by following formulation

$$F(\boldsymbol{r},t) = F(x,y,z,t) = \boldsymbol{\eta}(x,y,t) - z = 0. \quad (23)$$

The kinematic free surfce boundary condition (KFSBC) shows no flow through the free surface.

$$D_t\boldsymbol{F}(\boldsymbol{r},t) = \partial_t\boldsymbol{F} - \nabla\boldsymbol{\Phi}\ \cdot\nabla\boldsymbol{F} = 0, \quad (24)$$

concerning the level function on x,y plane (at z=0), the free surface elevation η satisfies KFSBC

$$\partial_t \boldsymbol{\eta} = \partial_z \boldsymbol{\Phi} - \nabla_h \boldsymbol{\Phi} \cdot \nabla_h \boldsymbol{\eta} = 0, \quad 25)$$

where ∇_h denotes spatial gradient of horizontal x,y plane. The dynamic free surface boundary condition (DFSBC) is given by Bernoulli's equation.

$$\partial_t \boldsymbol{\Phi} = g\boldsymbol{\eta} + \frac{1}{2}|\nabla\boldsymbol{\Phi}|^2 - \frac{p_a}{\rho_w} = 0, \quad (26)$$

where g is gravity, p_a denotes pressure and ρ_w denotes density of fluid. Similar to the case of free surface, the kinematic and dynamics boundary condition on the fluid structure interface can be written as in Eq.(25,26). Only the particular coordinate system should be introduced, the ς-axis is normal to the plane (ξ, ϑ). The movement of the fluid structure interface is introduced as $\boldsymbol{\chi}(\xi,\vartheta,\varsigma,\mathrm{t}) = \boldsymbol{\chi_0}(\xi,\vartheta,\varsigma) + \boldsymbol{u}(\xi,\vartheta,\varsigma,\mathrm{t})$, where $\boldsymbol{\chi_0}(\xi,\vartheta,\varsigma)$ denotes the position of interface at rest and $\boldsymbol{u}(\xi,\vartheta,\varsigma,\mathrm{t})$ denotes the displacement of the interface. Let $\boldsymbol{\chi_\varsigma}(\xi,\vartheta,\varsigma,\mathrm{t})$ is the movement of interface in ς-direction. The kinematic boundary condition describes no flow through the interface

$$\partial_t \boldsymbol{\chi_\varsigma} = \partial_\varsigma \Phi - \nabla_s \Phi \cdot \nabla_s \boldsymbol{\chi_\varsigma}, \quad (27)$$

where ∇_s denotes surface gradient on (ξ, ϑ) coordinate. On the boundary condition of sea bed, the $\partial_t \boldsymbol{\chi_\varsigma} = 0$ describes no movement of sea bed, oppositely, if the movement of sea bed is concerned, the Eq.(27) can be used for the interface such as zunami wave. The dynamics boundary condition is given by Bernoulli's equation. Only the interaction forces between fluid and structure have to be included, containing stress vector $\boldsymbol{\tau_\varsigma}$.

$$\partial_t \boldsymbol{\Phi} = g(z + \eta + \boldsymbol{u}_z) + \frac{1}{2}|\nabla\boldsymbol{\Phi}|^2 - \frac{\tau_\varsigma + p_a}{\rho_w}, \quad (28)$$

where $\boldsymbol{u}_z$ denotes z-component of displacement in global coordinate system (x,y,z).

The random finte depth wave is also developed in this research work, in order to make the possibility of including random wave and fully nonlinear wave into the computation. The details of mathematical model will not be shown here again, however these have already been published and are available in references.

Discretized Formulations with BEM

The Laplace's equation is initially written in the integral form by using Green's second identity, which yields the boundary integral equation [6,7].

$$C(\boldsymbol{x_r})\,\Phi(\boldsymbol{x_r}) + \int \Phi(\boldsymbol{x})\,\partial_n G(\boldsymbol{x},\boldsymbol{x_r})d\Gamma(x) - \int \partial_n \Phi(\boldsymbol{x})\,G(\boldsymbol{x},\boldsymbol{x_r})d\Gamma(x) = 0, \quad (29)$$

where $\boldsymbol{x_r}\,(x_r, y_r, z_r)$ denotes the refrence point and $\boldsymbol{x}(x,y,z)$ denotes the arbitary point on the boundary. The term $C(\boldsymbol{x_r})$ is obtained by

$$C(\boldsymbol{x_r}) = \frac{\alpha}{4\pi}, \quad (30)$$

where $\boldsymbol{\alpha}$ is the solid angle on the boundary, to compute solid angle, please refer to reference. The corresponding Green's function for 3D case is given by

$$\boldsymbol{G}(\boldsymbol{x},\boldsymbol{x_r}) = \frac{\mathbf{1}}{\mathbf{4}\boldsymbol{\pi}|\boldsymbol{x}-\boldsymbol{x_r}|}, \quad (31)$$

The BIE in Eq.(29) is discretized by BEM, and meshes are necessary only on the surface (2D) of boundary for 3D domain of fluid. The variables on the boundary node are Φ and $\partial_n\Phi$, in each node one variable should be defined to complete the boundary value problem.

$$\boldsymbol{A}\,\Phi = \boldsymbol{B}\partial_n\Phi, \quad (32)$$

Eq.(32) above is rewriten by setting known value $\boldsymbol{p}_k$ on the right hand side and unknow value $\boldsymbol{p}_u$ on the left hand side with corresponding matrix $\boldsymbol{H}$and $\boldsymbol{G}$.

$$\boldsymbol{H}\boldsymbol{p}_u = \boldsymbol{G}\boldsymbol{p}_k. \quad (33)$$

In order to reduce the CPU time, the Fast Multipole method is also implemented here, more details about Fast Multipole method for BEM please refer to reference and reference therein.

Soil Dynamics of Sea Bed

Mathematical Formulations of Sea Bed

The formulations of soil dynamics for sea bed will be explained here brieftly, for more details please refer to [6,9]. The sea bed is modelled as continua based on linear elastic theory. The stress ($\boldsymbol{\sigma}$) and strain ($\boldsymbol{\epsilon}$) field are represented by Hooke's law. The constitutive relation can be written as

$$\boldsymbol{\sigma} = \boldsymbol{E\epsilon}, \quad (34)$$

where $\boldsymbol{E}$ is elasticity matrix, the strain field can be obtained by strain-displacement relation.

$$\boldsymbol{\epsilon} = \boldsymbol{Pd}, \quad (35)$$

The differential operator $\boldsymbol{P}$ is combined in cartesian coordinate system. Based on Newton's law, the dynamics equilibrium equation in frequency domain can be obtained as

$$\boldsymbol{P^T\sigma} + \boldsymbol{b} = -\omega^2\boldsymbol{d}, \quad (36)$$

while Eq.(36) can also be written in time domain as

$$\boldsymbol{P^T\sigma}(t) + \boldsymbol{b}(t) = \rho\partial_t^2\boldsymbol{d}(t), \quad (37)$$

where stress $\boldsymbol{\sigma}$, body forces $\boldsymbol{b}$ and displacement $\boldsymbol{d}$ are in time domain.

Discretized Formulations with FEM

The dynamics equilibrium equation is dicretized based on the conventional finite element methods. Here the

sea bed is considered into two regions, in which a finite region represents soil close to the structure, including some parts of structure (near field) and an infinite region represents unbounded soil far from the structure (far field). The discrete form of Eq.(37) is given by

$$\boldsymbol{M}_c\partial_t^2\boldsymbol{d}(t)+\boldsymbol{K}_c\boldsymbol{d}(t)=\boldsymbol{f}_c(t), \quad (38)$$

where $\boldsymbol{M}$ denotes mass matrix and $\boldsymbol{K}$ denotes stiffness matrix while $\boldsymbol{f}$ is force vector given by

$$\boldsymbol{M}_c=\begin{bmatrix}\boldsymbol{M}_{ss} & \boldsymbol{M}_{sb}\\ \boldsymbol{M}_{bs} & \boldsymbol{M}_{bb}-\gamma\Delta t\boldsymbol{M}_o^{\infty}\end{bmatrix}, \boldsymbol{K}_c=\begin{bmatrix}\boldsymbol{K}_{ss} & \boldsymbol{K}_{sb}\\ \boldsymbol{K}_{bs} & \boldsymbol{K}_{bb}\end{bmatrix},$$
$$\boldsymbol{f}_c=\begin{bmatrix}\boldsymbol{f}_s(t)\\ \boldsymbol{f}_b(t)-\boldsymbol{r}_b(t)\end{bmatrix},.$$

The subscript c denotes the coupled system of near field/far field. The subscript s and b are inside domain and at the boundary respectively. The effect of infinite domain will be included in $\gamma\Delta t\boldsymbol{M}_o^{\infty}$ term with γ paramter in Hilber- Hughes- Taylor (HHT) time integration scheme. The $\boldsymbol{r}_b(t)$ denotes interaction forces from infinite domain.

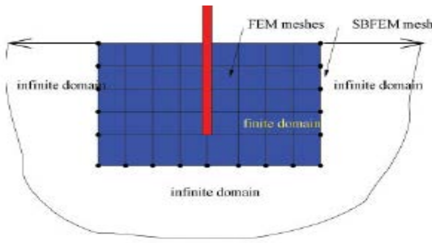

FIG. 8 FINITE AND INFINITE OF SEA BED

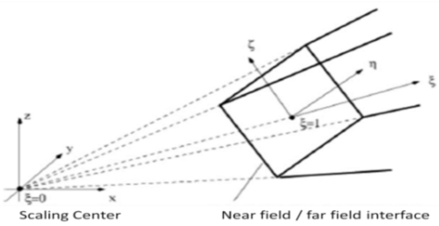

FIG. 9 SCALED BOUNDARY TRANFORMATION

Coupled with SBFEM for Unbounded Soil

In order to include the effect of unbounded soil, the coupled near field/far field is developed as mentioned in previous section. The far field is involved here by using the so-called Scaled Boundary Finite Element Method (SBFEM), and the concept of geometrical similarity is implemented associated with conventional approaches of FEM. Initially the near field soil (including some part of srtucture) must be discretized, FE-meshes will be constructed in this part, while SBFE-meshes can be obtained by using FE-meshes on the boundary, see in Fig. (8). The FE-meshes (on the boundary) are transformed into the so-called scaled boundray coordinate system (η,ζ,ξ), see in Fig. (9). The axis η,ζ is described in the circumferential direction only on the boundary, while the third axis ξ contains a scaling factor from center. This scaled boundary coordinate permits a numerical treatment in circumferential direction η,ζ based on weighted residual technique. The PDE in Eq.(36) is transformed into ODE in radial coordinate ξ ,yield as

$$\boldsymbol{E}_0\left(\xi^2\partial_{\xi\xi}^2\boldsymbol{d}+2\xi\partial_\xi\boldsymbol{d}\right)-\boldsymbol{E}_1\xi\partial_\xi\boldsymbol{d}\quad+\boldsymbol{E}_1^T\left(\xi\partial_\xi\boldsymbol{d}+\boldsymbol{d}\right)$$
$$-\boldsymbol{E}_2\boldsymbol{d}+\omega^2\boldsymbol{M}_0\xi^2\boldsymbol{d}+\xi\boldsymbol{f}_t+\xi^2\boldsymbol{f}_b=0, \quad (39)$$

where $\boldsymbol{E}_0,\boldsymbol{E}_1,\boldsymbol{E}_2,\boldsymbol{M}_0$ are the coefficient matrix which are independent of ξ. The $\boldsymbol{f}_t,\boldsymbol{f}_b$ denote traction forces and body forces.

Continously, the method of vitual work is used to derive the SBFEM formulation in term of dynamics stiffness $\boldsymbol{S}^{\infty}$of infinite domain.

$$(\xi^{-1}\boldsymbol{S}^{\infty}+\boldsymbol{E}_1)\boldsymbol{E}_0^{-1}(\xi^{-1}\boldsymbol{S}^{\infty}+\boldsymbol{E}_1^T)-\xi^{-1}\boldsymbol{S}^{\infty}-$$
$$\xi\partial_\xi(\xi^{-1}\boldsymbol{S}^{\infty})-\boldsymbol{E}_2+\xi^2\boldsymbol{M}_0=0. \quad (40)$$

The Eq.(40) still in frequency domain ($\boldsymbol{S}^{\infty}=\boldsymbol{S}^{\infty}(\omega)$). In order to transform Eq.(40) into time domain, the inverse Fourier transformation is used to derive the formulation in time domain. It is not necessary to go in details of deriving of formulation here, autors refer to references. Finally the acceleration of unit impulse response matrix $\boldsymbol{M}^{\infty}(t)$ can be obtained by the following formulation

$$\boldsymbol{M}^{\infty}(t)=\boldsymbol{U}^T\widehat{\boldsymbol{M}}^{\infty}(t)\boldsymbol{U}, \quad (41)$$

where $\widehat{\boldsymbol{M}}^{\infty}(t)$ can be determined by solution of convolution integral of dynamics formulation. $\boldsymbol{U}^T\boldsymbol{U}$ are decomposition of coefficient matrix $\widehat{\boldsymbol{E}}_{\boldsymbol{0}}$.

In Eq.(38), the interaction forces $\boldsymbol{r_b}(t)$ at near field/far field interface are required which could be obtained by means of convolution integral, here we show the discrete form of these formulation

$$\boldsymbol{r_b}(t)=\sum_{j=1}^{n}\boldsymbol{M}_{n-j}^{\infty}\int_{(j-1)\Delta t}^{j\Delta t}\partial_t^2\boldsymbol{d}(\tau)\,d\tau$$
$$=\sum_{j=1}^{n}\boldsymbol{M}_{n-j}^{\infty}\left(\partial_t\boldsymbol{d}_j-\partial_t\boldsymbol{d}_{j-1}\right). \quad (42)$$

For large number of $\boldsymbol{n}$ (i.e., long time simulation) the direct solution might be limited due to the very time consuming. The recursive procedure is used for approximation this forces with reduced computing time, in details of recursive procedure the autor refer to reference and reference therein.

Coupled Multi-physics Model

The general pattern is that in each subsystem the dynamics are described by either pure differential equations (abstract ODE), such as for the structure Eq.(9), or by differential algebraic equations (abstract

DAE). The total coupled system as described before by the space-discretized version may be written as the following form

$$\partial_t \boldsymbol{\Phi} = \phi_\Phi(\boldsymbol{\Phi}, \boldsymbol{\eta}, \boldsymbol{\tau}, \boldsymbol{d}), \quad (43)$$

$$\partial_t \boldsymbol{\eta} = \phi_\eta(\boldsymbol{\Phi}, \boldsymbol{\eta}, \boldsymbol{\tau}, \boldsymbol{d}), \quad (44)$$

$$0 = \psi_{\boldsymbol{\Phi},\boldsymbol{\eta}}(\boldsymbol{\Phi}, \boldsymbol{\eta}, \boldsymbol{\tau}, \boldsymbol{d}), \quad (45)$$

$$\boldsymbol{M}(\boldsymbol{d})\partial_t^2 \boldsymbol{d} + \boldsymbol{f}_{\boldsymbol{int}}(\partial_t \boldsymbol{d}, \boldsymbol{d}) = \phi_{\boldsymbol{s}}(\partial_t \boldsymbol{d}, \boldsymbol{d}, \boldsymbol{\Phi}, \boldsymbol{\eta}), \quad (46)$$

$$0 = \Psi_{\mathbf{fsi}}(\boldsymbol{\Phi}, \boldsymbol{\eta}, \boldsymbol{\tau}, \boldsymbol{d}), \quad (47)$$

$$\boldsymbol{M}(\boldsymbol{d})\partial_t^2 \boldsymbol{d} + \boldsymbol{f}_{\boldsymbol{int}}(\partial_t \boldsymbol{d}, \boldsymbol{d}) = \phi_{\boldsymbol{b}}(\partial_t \boldsymbol{d}, \boldsymbol{d}, \boldsymbol{\Phi}, \boldsymbol{\eta}), \quad (48)$$

$$0 = \Psi_{\mathbf{ssi}}(\boldsymbol{\tau}, \boldsymbol{d}), \quad (49)$$

$$\partial_t \boldsymbol{x} = \phi_w(\boldsymbol{d}, \partial_t \boldsymbol{d}), \quad (50)$$

$$0 = \psi_{\mathbf{x}}(\boldsymbol{\tau}, \boldsymbol{d}, \partial_t \boldsymbol{d}). \quad (51)$$

The Eq.(43)-Eq.(51) describe all subsystem of modeling, however, the modeling of subsystems can be changed without difficulty, i.e. fluid modeling can be changed from incompressible to compressible, while the coupling procedure stays the same but only subsystem is changed. To sovle them in time domain, they have to be solved based on iterative coupling procedure (partitioned method). The coupled algorithms are described here with the general flow of information. The subsystems are separated softwares, so called software components, coupled via the Component Template Library (CTL) used as the middle-ware in order to communicate with all the different software components. The coupled algorithms are described in the following simple way, see also Fig. (10).:

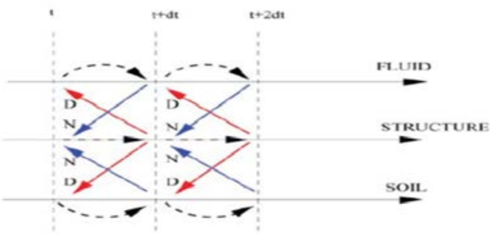

FIG. 10 COULING PROCEDURE FOR ENTIRE SYSTEM

At the current time step, the hydrodynamics quantities are computed with the PC-algorithm, termed as predicted values. This involves the solutions of Laplace's equation for each of the fluid domains. Now the hydrodynamic forces can be computed at the fluid-structure interface, and they are passed to the structure at the current time (Neumann data (labeled N). The structure system is integrated with these forces. The computed displacements change the fluid domain, the structural velocities are Dirichlet data for the fluid domains (labelled D) in Fig. (10) when passing back to the fluid. The iteration then goes back to the first step. This describes the fluid-structure coupling.

A similar coupling exists between structure and soil. The structure passes displacements (Dirichlet data) to the soil through the soil-structure interface. The dynamics of soil are solved with the HHT method and forces (Neumann data) are returned to the structure. The structure gets the corresponding forces from the coupling interface from soil and fluid. A new Newmark trial-step can be computed.

Also similarly coupled with the aerodynamics and structure, the dirichlet data is given from the structure part at the coupling area (here it is on the blade). The aerodynamics are solved and compute the aerodynamics forces. It returns the aerodynamic forces as the Nuemann data to the structure component to complete the structure dynamics. The iteration loops can continue in parallel until the residuum is sufficiently small.

Software Component

As in the coupling multi-physic model, there are many physical domains that have to be coupled. In each model, the corresponding software has to be used as the component of coupled systems. They are implemented in the different ways. The structural dynamics subsystem, the nonlinear large displacement modelling is used and discretized with FEM. The main code of this component is implemented in MatLab and some parts which take more CPU time are embeded with C functions. It works as the normal command line in MatLab, but it runs on C code.

The aerodynamics subsystem, the blade element momentum theory is used combine the stochatic wind field. This part is implemented in MatLab and communication with the structural part with the Matlab function. The hydrodynamics subsystem as the potential flow with the stochastic wave field, the main code of this is implemented in MatLab. Just only the part of solving Laplace's equation, we implemented the fast multipole-code FastLap (it is written in Fortran). To communicate Matlab code, the embedded C-functions is also used here.

The soil dynamic subsystem is modelled as the near-field and far-field model. The near-field is discretized by FEM, while the far-field is discretized with the so–called scaled boundary finite element method (SBFEM). The FEM is implemented with the Felt code (it is written in C) and the SBFEM is implemented with the similar code (it is written in Fortran) .

For the realization of this coupled simulation, graphically depicted in Fig. (11), we have chosen the

concept of software-components. Here a component is a set of software which consists of a well defined interface and an implementation. Interface and implementation are connected through a communication channel. In this way, the usage of a component is independent of its location.

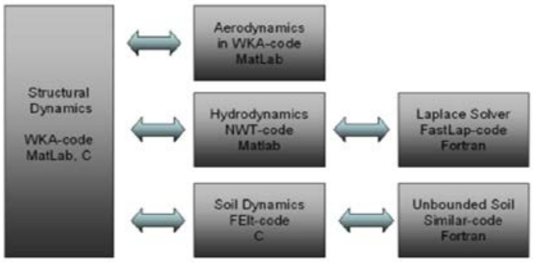

FIG. 11 SOFTWARE COMPONENT

The middle-ware used to implement the component technology is the Component Template Library (CTL) based on C++ generic template programming. It can be used to realise distributed component-based software systems. This library serves as an easy-to-use programming environment for distributed applications in an abstract manner, but its main focus is to transform existing C/C++ or FORTRAN libraries to remotely accessible software components. As underlying communication protocols MPI, PVM, or directly sockets, as well as dynamic linkage and threading are supported.

Simulation Results

Firstly, we show the numerical testing of soil subsystem coupling with tower (no effect rotor) in order to study the unbounded soil model with conpled FEM/SBFEM as explained in section of soil dynamics of sea bed.

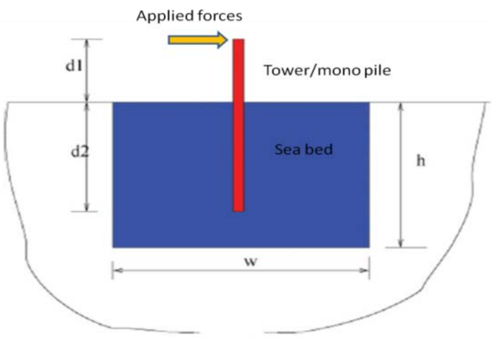

FIG. 12 DOMAIN OF TESTING MONO PILE

The monopile is located at the depth d2 = 20 m into finite domain of the soil, in which the depth of the soil domain h = 30 m. and domain width w = 20 m.. The length of the tower is measured from the surface of the soil d1 = 80 m. Horzontal force is applied on the top of tower. The dynamics equation of the soil is solved with the HHT method combine with the constant time interval 0.005 sec.

The result shows effect of unbounded soil on the movement of structure, see Fig. (13). The amplitude of displacement decreases along the time, meaning that the energy is damped due to unbounded soil, which is very physically reasonable. Therefore this FEM/ SBFEM is suitable for our entire simulation of off shore wind turbine. For other couple subsystem such as wind-structure or wave structure, we have also tested the coupled subsystem separately and these have been published. The entire model of offshore wind turbine have simulated based on the dynamics coupling procedure as described before. Concernig the simulation result, on the part of hydrodynamics, the wave formulations are written based on the fully nonlinear assumption as described before. The random wave fields are included by the stochastic process at the far from the structure. These waves are actually linear and the irregular wave charateristics are allowed to be involved as the summation of many differrent waves. The waves propagate and develop itself with the fully nonlinear formulation. The waves became nonlinear and its steepness increased during the propagation.

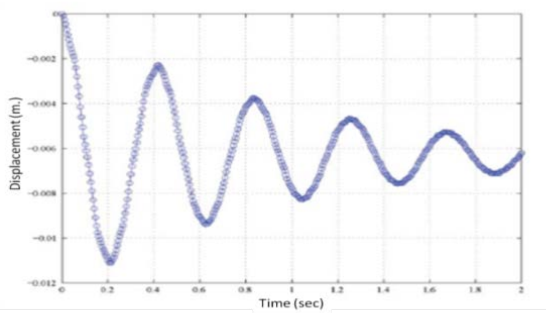

FIG. 13 TIME HISTORY OF DISPLACEMENT AT TOP OF TOWER

The irregular waves form remains during this propagation. When wave arrived the position close to structure, these waves were developed to become nonlinear and irregular waves. The waves run through the structure and pass away, while some waves are reflected by the effect of structure vibration.

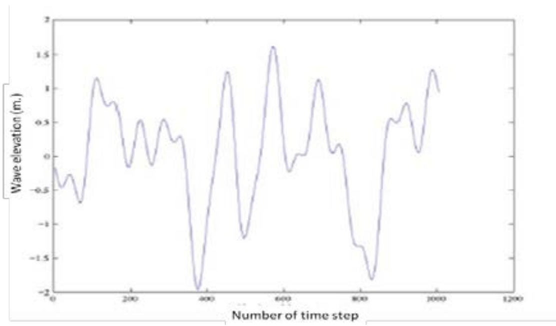

FIG. 14 IRREGULAR WAVE NEAR THE STRUCTURE

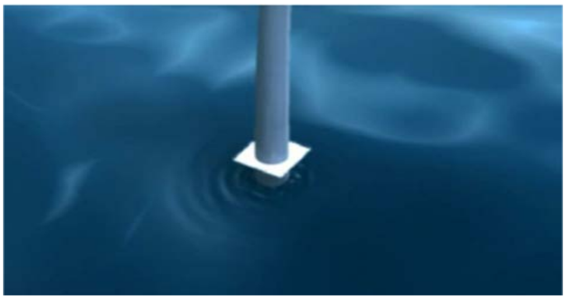

FIG. 15 VISUALIZATION OF WAVE INTEACTING STRUCTURE

Fig. (15) shown the nonlinear wave interacting the tower, and the reflection wave can be observed due to structure vibration. Also the irregular wave form can also be found consequently as shown in Fig. (14).

Considering the result on rotor blade and tower, the result shows the irregular form of deformation, resulting from irregular form of wind and wave. The deformation of rotor blade and tower are shown in Fig. (17), while the displacement of rotor is shown in Fig. (16).

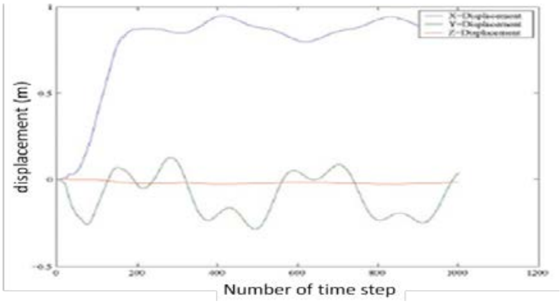

FIG. 16 DISPLACEMENT OF ROTOR BLADE

FIG. 17 VISUALIZATION OF BLADE AND TOWER

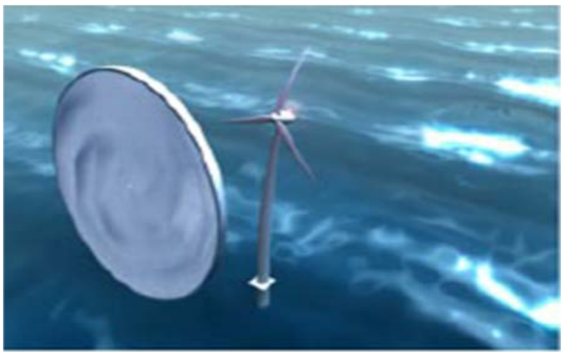

FIG. 18 VISUALIZATION OF OFFSHORE WIND TURBINE

Fig. (18) shows the visualization of entire system of offshore wind turbine. The deformation rotor blade and tower can be observed as their movements are very irregular form. In front of rotor, we present the velocity of the wind field, and this wind velocity is very random and presents irregular form of wind forces acting rotor blade.

Conclusions

In this paper, the model of an offshore wind turbine was presented consisting of the aerodynamics of the wind, structure dynamics of the turbine component, the hydrodynamics of the ocean wave and the soil dynamics of the sea bed. A concept of modelling offshore wind turbines is to develop the sub-system modelling initially separately, and then coupling the entire model by using partitioned method. The structure modelling of offshore wind turbines is modelled by the nonlinear beam element and discretized with FEM. The random of wind field is included based on the blade element momentum theory and dynamics stall model. The hydrodynamics of the ocean wave is modelled as the random finite depth wave. The fluid dynamics is described by the BIE of Laplace's equation and discretised by BEM. The soil can be modelled by the finite domain and infinite domain. The finite domain is discretized by finite FEM, and the infinite domain can be included by SBFEM.

The software components are communicated with CTL middle ware. The simulation of coupled multi-physics model was performed in time domain and reasonable result was presented physically. However in either sub-modelling the complexity could also be extended or increased in order to come closer to the nature, which would be outlook of our research and will be presentedlater.

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